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REMOTE SENSING OF EARTH TERRAIN

Under the sponsorship of the NASA Contract NAGW-1617, we published (64) refereed journal and conference papers for the research on remote sensing of earth terrain. The following is a summary of recent research findings.

Radiative Transfer Model for Active and Passive Remote Sensing of Vegetation Canopy

Based upon the vector radiative transfer (RT) equations, we present a theoretical model for calculating the radar backscattering coefficients and the brightness temperatures of multi-layered vegetation canopy for active and passive microwave remote sensing, respectively. Effects of the underlying rough surface have been taken into account through the Geometrical Optics approximated coupling matrix in the radiative transfer formulation. The solutions of the RT equations are derived iteratively to the second order for the active case, and first order for the passive case. The particular physical scattering or emission mechanism associated with each term in the iterative solution is identified. Numerical examples for the backscattering coefficients and brightness temperatures of a two-layer vegetation-like medium are presented.

Vegetation canopy can be modeled as either a mixture of multiple-species discrete scatterers described by a certain size, shape, and orientation distributions, or a continuous random medium characterized by correlation functions. In this paper, the phase matrix and emission vector under both approaches are evaluated for a collection of randomly oriented spherical inhomogeneities. Numerical comparison for the resulting backscattering coefficients is performed. The relation between the correlation lengths used in the continuous random medium model to describe the shape of inhomogeneities and the dimensions of the scatterer in the discrete model are discussed. More specifically, the scattering amplitudes, attenuation rates, and the albedo's, or the amplitude ratio between scattering and attenuation, predicted under both approaches are compared, and the causes giving rise to the discrepancies in the scattering and emission computation are identified.

Polarimetric Thermal Emission from Rough Ocean Surfaces

A numerical study of the polarimetric thermal emission from ocean surfaces randomly rough in one dimension using a Monte Carlo technique is presented. In this study, a set of finite length surface profiles with desired statistics was generated using a spectral method. Each surface was extended periodically to create an infinite rough surface, and the thermal emission was computed using the extended boundary condition method (EBC) and the method of moments (MOM).

the results from the set of surfaces were then averaged to obtain the Monte Carlo estimate of polarimetric thermal emission. The surface statistics chosen were intended to model a wind perturbed ocean surface in the X to K_u band microwave region. The results of the study show that the third Stokes parameter, U_B , is sensitive to the azimuthal angle between the surface periodicity and the looking angle, the rms height of the surface, and the surface power law spectrum slope, and that this parameter is insensitive to variations in polar angle, permittivity, and surface spectrum high frequency content.

Polarimetric Passive Remote Sensing of Ocean Wind Vectors

This study is on the theory of polarimetric passive remote sensing of wind-generated sea surfaces and the potential application of polarimetric radiometry to ocean surface winds. The small perturbation method (SPM), derived to second order, is applied to the Stokes vectors of the thermal emission from random rough dielectric surfaces described by anisotropic directional spectra. To verify the accuracy of the SPM, a Monte Carlo simulation is performed to calculate the Stokes vectors of the emission from the simulated one-dimensional random rough surfaces with a power-law spectrum for various observation angles and surface parameters. The theoretical results of the SPM for all four Stokes parameters are in excellent agreement with the numerical results obtained from the Monte Carlo simulation. Moreover, the second-order coherent fields are indispensable in the theoretical evaluation of the third and fourth Stokes parameters. Otherwise, the reflectivities of random rough surfaces would be significantly over-estimated, and the signs of the third and fourth Stokes parameters would be incorrect. The SPM is then applied to small-scale sea surface described by an empirical surface spectrum. Theoretical model functions of the Stokes parameters are illustrated, and the inversion of surface wind vectors from polarimetric brightness data is investigated. The results indicate that polarimetric radiometry allows wind vector measurements with only one azimuthal observation angle, which is made possible by the different azimuthal dependence between the third Stokes parameter and the first two Stokes parameters. Radiometers with a single-azimuth-observation design will not only simplify the antenna-beam-scanning mechanism, but also will be free from the complexity associated with the data co-registration required for multiple-azimuth-observation designs.

Polarimetric Thermal Emission from Periodic Water Surfaces

Experimental results and theoretical calculations are presented to study the polarimetric emission from water surfaces with directional features. It is observed that the measured Stokes parameters of corrugated fiberglass-covered water surfaces are functions of azimuth angles and agree very well with theoretical calculations. The theory, after verified by the experimental data, was then

used to calculate the Stokes parameters of periodic surfaces without fiberglass surface layer and with rms height of the order of wind-generated water ripples. The magnitudes of the azimuthal variation of the calculated emissivities at horizontal and vertical polarizations corresponding to the first two Stokes parameters are found to be comparable to the values measured by airborne radiometer and SSM/I. In addition, the third Stokes parameter not shown in the literature is seen to have approximately twice the magnitude of the azimuth variation of either T_h or T_v . The results of this paper indicate that passive polarimetry is a potential tool in the remote sensing of ocean wind vector.

Layer Model with Random Spheroidal Scatterers for Remote Sensing of Vegetation Canopy

A layer model is developed and applied to interpret radar backscattering coefficients at 5.3 GHz for a soybean canopy. The canopy is modeled as a random medium containing spheroidal scatterers for the leaves. The data were taken over an extended time period from early to late stage of the vegetation. The theoretical results and the experimental data are in good agreement. The lateral correlation length is observed to be highly correlated with the canopy fractional volume. With consideration of the interrelations among biophysical parameters, the model is then used to simulate backscattering coefficients under various conditions. The results provide sensitivity domains of radar responses to soil moisture and vegetation biomass for inversion assessment. Furthermore, the polarization signatures of the vegetation canopy are synthesized to illustrate structural information conveyed by polarimetric data.

Application of Theoretical Models to Active and Passive Remote Sensing of Saline Ice

The random medium is used to interpret the polarimetric active and passive measurements of saline ice. The ice layer is described as a host ice medium embedded with randomly distributed inhomogeneities, and the underlying sea water is considered as a homogeneous half-space. the scatterers in the ice layer are modeled with an ellipsoidal correlation function. The orientation of the scatterers is vertically aligned and azimuthally random. The strong permittivity fluctuation theory is employed to calculate the effective permittivity and distorted Born approximation is used to obtain the polarimetric scattering coefficients. We also calculate the thermal emissions base on the reciprocity and energy conservation principles. The effects of the random roughness at the air-ice, and ice-water interfaces are accounted for by adding the surface scattering to the volume scattering return incoherently. The above theoretical model, which has been successfully applied to analyze the radar backscatter data of the first-year sea ice near Point Barrow, AK, is used to interpret the measurements performed in the CRRELEX program.

Radiative Transfer Theory for Polarimetric Remote Sensing of Pine Forest

The radiative transfer theory is applied to interpret polarimetric radar backscatter from pine forest with clustered vegetation structures. To take into account the clustered structures with the radiative transfer theory, the scattering function of each cluster is calculated by incorporating the phase interference of scattered fields from each component. subsequently, the resulting phase matrix is used in the radiative transfer equations to evaluate the polarimetric backscattering coefficients from random medium layers embedded with vegetation clusters. Upon including the multi-scale structures, namely, trunks, primary and secondary branches, as well as needles, we interpret and simulate the polarimetric radar responses from pine forest for different frequencies and looking angles. The preliminary results are shown to be in good agreement with the measured backscattering coefficients at the Landes maritime pine forest the MAESTRO-1 experiment.

Scattering of Electromagnetic Waves from a Dense Medium Consisting of Correlated Mie Scatterers with Size Distributions and Applications to Dry Snow

The scattering of a plane electromagnetic wave obliquely incident on a layer of dense medium consisting of dielectric spherical particles of finite sizes and with size distributions is studied. The spherical particles are of sizes comparable to wavelength so that Mie scattering is used to describe the single particle scattering characteristics. The coherent wave is studied with quasicrystalline approximation using the cross pair distribution functions of multiple size governed by Percus-Yevick approximation. The incoherent scattered wave is calculated with the distorted Born approximation with the result expressed in terms of a product of the T-matrices of particles of different sizes and permittivities and the Fourier transform of the cross pair distribution functions. The coherent wave effective propagation constants, the attenuation rates and the backscattering coefficients are illustrated numerically, with examples chosen to illustrate microwave and millimeter wave scattering from snow cover in the frequency range of 5 GHz to 95 GHz, and mean grain radius between 0.03 cm to 0.09 cm. Salient features of the numerical results for scattering from snow with size distribution are: (1.) Correlated dense medium scattering is less than independent scattering at low frequency, a fact that is consistent with controlled laboratory experiment. (2.) Scattering from dense medium of a Rayleigh size distribution with an average radius can be much larger than the case of monodisperse particles of the sizes identical to that average radius. (3.) The scattering attenuation rate increases rapidly with frequency at low frequency regime and begins to level off at high frequency regime. (4.) The coherent wave scattering attenuation rate is large in snow at frequencies above 15 GHz indicating large optical thickness and the important of multiple scattering. Comparisons with extinction measurements of dry snow at 18 GHz, 35 GHz, 60 GHz, and 90 GHz are made.

Variance of Phase Fluctuations of Waves Propagating through a Random Medium

As an electromagnetic wave propagates through a random scattering medium, such as a forest, its energy is attenuated and random phase fluctuations are induced. The magnitude of the random phase fluctuations induced is important in estimating how well a Synthetic Aperture Radar (SAR) can image objects within the scattering medium. The two-layer random medium model, consisting of a scattering layer between free space and ground, is used to calculate the variance of the phase fluctuations induced between a transmitter located above the random medium and a receiver located below the random medium. The scattering properties of the random medium are characterized by a correlation function of the random permittivity fluctuations. The effective permittivity of the random medium is first calculated using the strong fluctuation theory, which accounts for large permittivity fluctuations of the scatterers. The distorted Born approximation is used to calculate the first-order scattered field. A perturbation series for the phase of the received field in the Rytov approximation is then introduced and the variance of the phase fluctuations is solved to first order in the permittivity fluctuations. The variance of the phase fluctuations is also calculated assuming that the transmitter and receiver are in the paraxial limit of the random medium, which allows an analytic solution to be obtained. Results are compared using the paraxial approximation, scalar Green's function formulation, and dyadic Green's function formulation. The effects studied are the dependence of the variance of the phase fluctuations on receiver location in lossy and lossless regions, medium thickness, correlation length and fractional volume of scatterers, depolarization of the incident wave, ground layer permittivity, angle of incidence, and polarization.

Polarimetric Signatures of a Canopy of Dielectric Cylinders Based on First and Second Order Vector Radiative Transfer Theory

Complete polarimetric signatures of a canopy of dielectric cylinders overlying a homogeneous half space are studied with the first and second order solutions of the vector radiative transfer theory. The vector radiative transfer equations contain a general nondiagonal extinction matrix and a phase matrix. The energy conservation issue is addressed by calculating the elements of the extinction matrix and the elements of the phase matrix in a manner that is consistent with energy conservation. Two methods are used. In the first method, the surface fields and the internal fields of the dielectric cylinder are calculated by using the fields of an infinite cylinder. The phase matrix is calculated and the extinction matrix is calculated by summing the absorption and scattering to ensure energy conservation. In the second method, the method of moments is used to calculate the elements of the extinction and phase matrices. The Mueller matrix based on the first order and second order multiple scattering solutions of the vector radiative transfer equation are calculated. Results from the two methods are compared. The vector radiative transfer equations, combined

with the solution based on method of moments, obey both energy conservation and reciprocity. The polarimetric signatures, copolarized and depolarized return, degree of polarization, and phase differences are studied as a function of the orientation, sizes, and dielectric properties of the cylinders. It is shown that second order scattering is generally important for vegetation canopy at C band and can be important at L band for some cases.

Branching model for vegetation

A branching model has been proposed for the remote sensing of vegetation. The frequency and angular response of a two-scale cylinder cluster are calculated to demonstrate the significance of vegetation architecture. The results indicate that it is necessary for theoretical remote sensing models to take into account the architecture of vegetation which plays an important role in determining the observed coherent effects. A two-scale branching model is implemented for soybean with its internal structure and the resulting clustering effects considered. Furthermore, at the scale of soybean fields, the relative locations of soybean plants is described by a pair distribution function. The polarimetric backscattering coefficients are obtained in terms of the scattering properties of soybean plants and their pair distribution. Theoretical backscattering coefficients are evaluated using two pair-distribution functions: independent scatterer and hole correction. Backscattering coefficients calculated by using independent-scatterer pair distribution are in good agreement with extensive data collected from soybean fields except for the data near normal incidence. It is found that the hole-correction approximation, which prevents two soybean plants from overlaying each other, is more realistic. By introducing destructive interference at small angles of incidence, it greatly improves the agreement between the model and these three data sets near normal incidence. Extension to a multi-scale branching model can be achieved by recursion of the two-scale modelling approach reported in this research.

In the past, when radiative transfer theory was applied to the modeling of vegetation, the average phase matrix of vegetation layer was approximated by an incoherent sum of the phase matrices of individual vegetation elements. However, it can be observed that most of vegetation species exhibits a branching structure, whose significance has been demonstrated by the frequency and angular response of a two-scale cylinder cluster. This indicates that it is necessary for theoretical remote sensing models to account for the architecture of vegetation.

In this research, radiative transfer theory is applied to vegetation with clustered structures. To take into account vegetation structure in the radiative transfer theory, the phase matrix of a vegetation cluster is calculated by incorporating the phase interference of scattered fields from every components. Subsequently, the resulting phase matrix is used in the radiative transfer equations

to evaluate the polarimetric backscattering coefficients from a layer of medium embedded with vegetation clusters. Theoretical results are illustrated for various kinds of vegetation clusters. It is found that the simulated polarization, frequency, and angular responses carry significant information regarding the structure of vegetation clusters, and also agree with the signatures observed in measured multi-frequency polarimetric synthetic aperture radar images.

In passive remote sensing of earth terrain, the radiative transfer (RT) theory has also been widely applied with various types of random medium models to interpret observation. Part of the advantages of the RT theory can be attributed to its simplicity in formulating the reflection and transmission in the presence of boundaries as well as in treating the scattering effect by the incoherent sum of the scattering from each individual scatterer. However, being restricted by this incoherent nature, the RT theory cannot properly take into account the coherent effect which becomes significant at lower frequency in the case of remote sensing of a structured vegetation canopy as observed in our active models.

In this research, we formulate the vector radiative transfer equation for passive microwave remote sensing of a vegetation canopy overlying a soil half-space, and study the calculated brightness temperatures resulting from microwave thermal emission based on the Gaussian quadrature numerical method. A randomly distributed stem-leave model is employed to construct the phase matrix such that the effects of coherence and multi-scale can be properly accounted for.

For polarimetric remote sensing, geophysical media are modeled as layers containing randomly embedded scatterers. In a medium such as vegetation canopy, the scatterers can have various shapes, sizes, and permittivities that are significantly distinct from the background medium. The model studied in this research will consider each type of the scatterers as a species which can take on a shape, size, and complex permittivity different from other species. The effective permittivity of the random medium is derived under the strong permittivity fluctuation theory and the polarimetric scattering coefficients are calculated for the layer configuration with the distorted Born approximation in the analytical wave theory which preserves the phase information.

The multiple species in the random medium are considered as randomly oriented ellipsoids and described by multiple three-dimensional ellipsoidal correlation functions. The variances and correlation lengths of the correlation functions characterize the fluctuation strengths and the physical geometry of the scatterers, respectively. The strong permittivity fluctuation theory is extended to account for the multiple species of ellipsoidal shape. In the random medium, a coincidence of an observation point with a source point gives rise to the singularity of the dyadic Green's function which is properly taken into account with exclusion volumes of the scatterers.

Polarimetric scattering properties of a remotely sensed medium are depicted with a covariance matrix whose elements are polarimetric scattering coefficients. The medium has a layer configuration: the top layer such as air is considered as homogeneous, the middle layer such as a vegetation canopy is random, and the underlying layer such as soil is a homogeneous half space. More random medium layers can also be introduced in the configuration to account for weather effect such as fog cover. The distorted Born approximation is then used with the effective permittivity to obtain the polarimetric covariance matrix. The result for the cross-polarized return σ_{hv} is non-zero even in the first order approximation. Due to the non-spherical shape and the random orientation of the scatterers, the correlation coefficient between the HH and VV returns has a magnitude differed from unity and a small phase. The scattering coefficients are also used to calculate the Mueller matrix for synthesis of polarization signatures. The copolarized signature of the random medium has a rather straight distortion track and a recognizable pedestal.

Polarimetric Passive Remote Sensing of Periodic Surfaces

To demonstrate the use of microwave polarimetry for passive remote sensing of azimuthally asymmetric surface features on the earth terrain, we have performed a series of theoretical analysis and experimental measurements for the polarimetric thermal emissions from periodic surfaces. In our recent research, the third Stokes parameter U for thermal emission from periodic surfaces has been shown to be zero when the observation direction is parallel or perpendicular to the direction of the corrugation, while becomes significant for observation directions between these two directions. Thus, the parameter U is related to the relative azimuthal angles of observation and symmetry axes of periodic surfaces. This implies that measurement of fully polarimetric emissions of all four Stokes parameters can be used to probe the symmetry axes of surface structures. In addition, the other measured Stokes parameters are also shown to be related to the height variations of periodic surfaces, and permittivities of the underlying medium.

To verify the theoretical findings, an experiment was designed and carried out by measuring the polarimetric thermal emissions from a triangularly corrugated soil surface. A triangular corrugation pattern was prepared on a surface of soil with known texture and moisture content. A 10 GHz radiometer operated at linear polarizations was then used to measure the brightness temperatures at different polar and azimuthal angles. The brightness temperatures corresponding to the first three Stokes parameters were measured. The fourth Stokes parameter V was not measured because the radiometer used could not measure the emission at circular polarizations. The measurements were made at horizontal, vertical, and 45° linear polarizations. Significant values of the brightness temperature corresponding to the third Stokes parameter U were observed in

various configurations (as high as 40 K for certain configurations). Theoretical analysis of the measurement data indicates that the appreciable values of U are caused by the azimuthal asymmetry of soil surfaces.

It is also observed from the experiment that T_{Bh} decreases, T_{Bv} increases, T_{Bp} decreases to a minimum at $\phi = 45^\circ$ and then increases as ϕ takes on the increased values. For U_B , the trend is similar to that of T_{Bp} . These general trends are supported by our theoretical predictions of the polarimetric brightness temperatures. The significant observation from this experiment is that the surface asymmetry can be detected with a measurement of U_B at a single azimuthal angle.

Composite Volume and Surface Scattering Model

Among the various theoretical models applied to study the electromagnetic wave scatterings from geophysical terrain, such as snow, ice, and vegetation canopy, the radiative transfer theory has drawn intensive attention in the microwave remote sensing society during the past years. In most of the scattering models, the volume scattering and the surface scattering effects have been investigated separately. Recently, there has been a growing interest in the construction of composite models which can take into account both types of scattering.

In this research, we study the first order iterative solution to the vector radiative transfer equations for a two-layer medium with a diffuse top boundary and an irregular bottom boundary of Gaussian roughness. The geometrical optics approach correction is used in formulating the boundary conditions. To demonstrate the utilities of the theory, we apply our formula with a phase matrix for randomly oriented spheroidal discrete scatterers to calculate the backscattering coefficients from soybean field in different growing stages and compare the results with the experimental measurements. Good agreement has been achieved for both the co-polarized and the cross-polarized data. It is observed that the presence of the rough surface can significantly enhance the backscattering at small incident angles and the levels of the cross-polarized return. The polarization signatures calculated based on the Mueller matrix show a straight distortion track and an observable pedestal. Numerical comparison to the backscattering coefficients calculated by using planar bottom boundary conditions with or without the incoherent addition of the rough surface effects are also made in this work.

Radar Image Classification

Classification of terrain cover using polarimetric radar is an area of considerable current interest and research. A number of methods have been developed to classify ground terrain types

from fully polarimetric synthetic aperture radar (SAR) images, and these techniques are often grouped into supervised and unsupervised approaches. Supervised methods, including both conventional Maximum Likelihood (ML) and more recent Multi-layer Perceptron classifiers, have yielded higher accuracy than unsupervised techniques, but suffer from the need for human interaction to predetermine classes and training regions. In contrast, unsupervised methods determine classes automatically, but generally show limited ability to accurately divide terrain into natural classes. In this research, a new terrain classification technique is introduced, utilizing unsupervised neural networks to provide automatic classification, but employing an iterative algorithm which overcomes the poor accuracy of other unsupervised techniques.

Several types of unsupervised neural networks are first applied to the classification of SAR images, and the results are compared with those of more conventional unsupervised methods. Neural Network approaches include Adaptive Resonance theory (ART), Learning Vector Quantization (LVQ), and Kohonen's self-organizing feature map. Conventional classifiers utilized are the migrating means clustering algorithm and the K-means clustering method. With both neural network and conventional classifiers, preprocessing is performed to reduce speckle noise and to stabilize the training process. Results show that LVQ is the best of the neural network techniques, and that this method outperforms all of the conventional unsupervised classifiers. The accuracy of even the LVQ technique, however, is seen to remain below that of supervised methods.

To overcome this poor accuracy, an iterative algorithm is proposed in which the SAR image is reclassified using a Maximum Likelihood (ML) classifier. Training of the ML classifier is performed using a training data set first classified by the above unsupervised method, thus, requiring no human intervention, and preserving the unsupervised nature of the overall classification scheme. The process is then repeated iteratively, training a second ML classifier using data classified by the first. It is shown that this algorithm converges rapidly, and significantly improves classification accuracy. Performance after convergence is seen to be comparable to that obtained with a supervised ML classifier, while maintaining the advantages of an unsupervised technique.

The new unsupervised and iterative algorithm developed in this research is applied to polarimetric SAR images of San Francisco and Beaufort sea ice, acquired by the Jet Propulsion Laboratory. The results obtained for this imagery using the new algorithm are compared with the results obtained with other techniques, and also with those obtained with single-feature classification. It is found in each case that the new fully polarimetric unsupervised algorithm yields classified images which compare closely with those obtained from optimally chosen, supervised algorithms.

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